Wireless & Mobile Networks

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Institute for Computing Systems Architecture

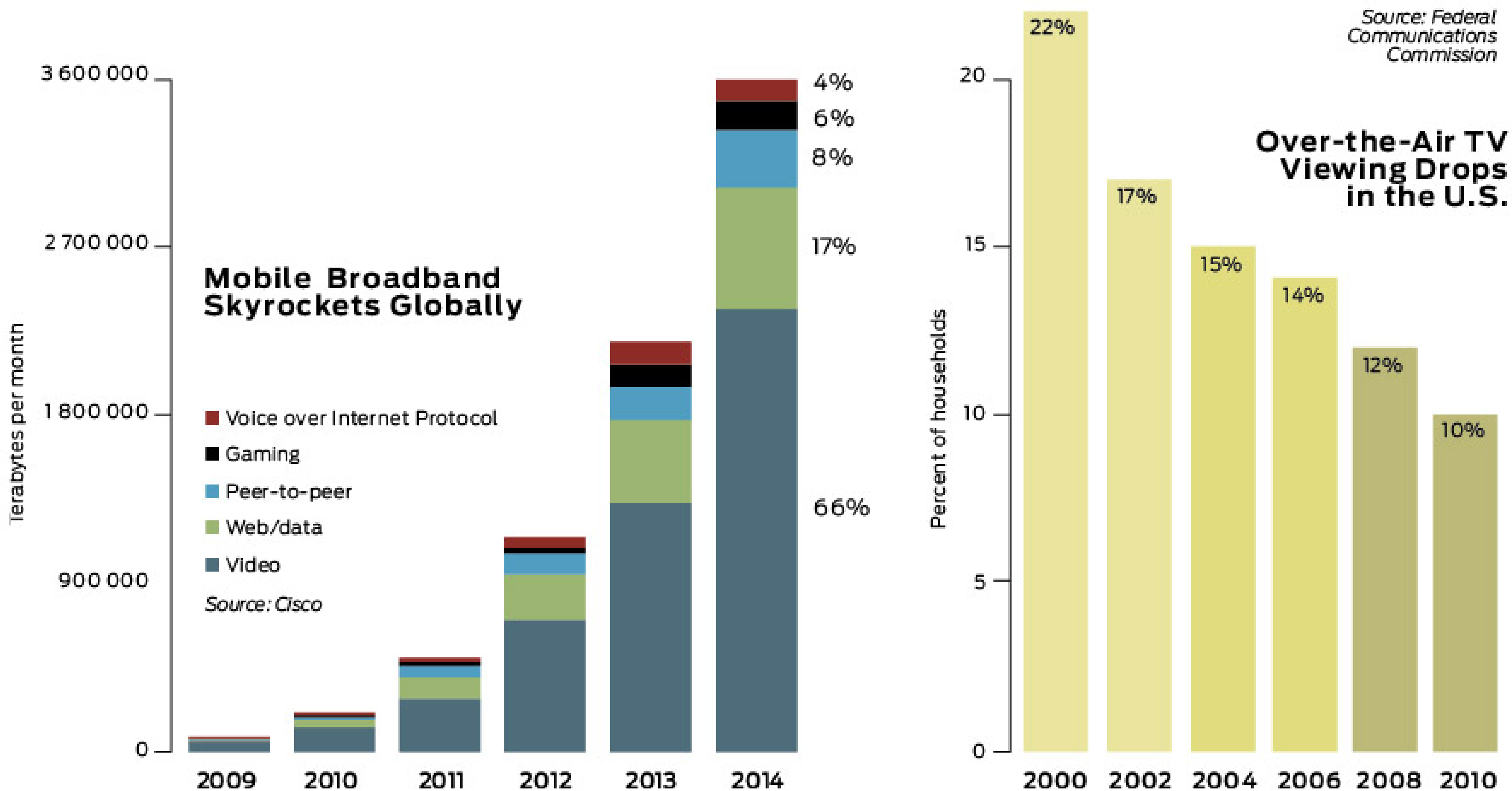
Wireless devices are everywhere

- Mobile computers (laptops, netbooks, tablets, handheld PCs, PDAs, …)
- Mobile phones (incl. smartphones)
- Wireless headsets, keyboards, mice, clickers, …
- Bus/train cards (e.g., Ridacard for Lothian Buses, London Oyster card)
- Cordless phones
- Remote controls
- Garage/car door openers, baby monitors, radio-controlled toys, …

An exciting field with remarkable success stories

- Mobile phone, a huge success
  - Global subscriptions will reach 5.3 billion by end of 2010, according to ITU estimates
  - Having a transformational impact in Africa and emerging economies
  - Around 5 million smartphones in use today
  - Data traffic has just exceeded voice traffic on mobile networks and doubling every six months

Mobile Broadband Traffic Trends



CHANGING TASTES: The amount of data being sent wirelessly over the Internet has shot up globally [left], while the small fraction of television-owning households that rely on over-the-air broadcasts has been steadily diminishing in the United States [right].

An exciting field with remarkable success stories

- Mobile phone, a huge success
  - Global subscriptions will reach 5.3 billion by end of 2010, according to ITU estimates
  - Having a transformational impact in Africa and emerging economies
  - Around 5 million smartphones in use today
  - Data traffic has just exceeded voice traffic on mobile networks and doubling every six months
- Widespread deployment of WiFi – homes, office, campuses, hotspots, …
  - WiFi, by far the most successful wireless Internet access technology
  - Community wireless networks mushrooming everywhere
- Several newer technologies starting to get deployed or in development – MIMO (802.11n), OFDMA (4G/LTE), TV white spaces, mmWave comms, cognitive radio networks, …

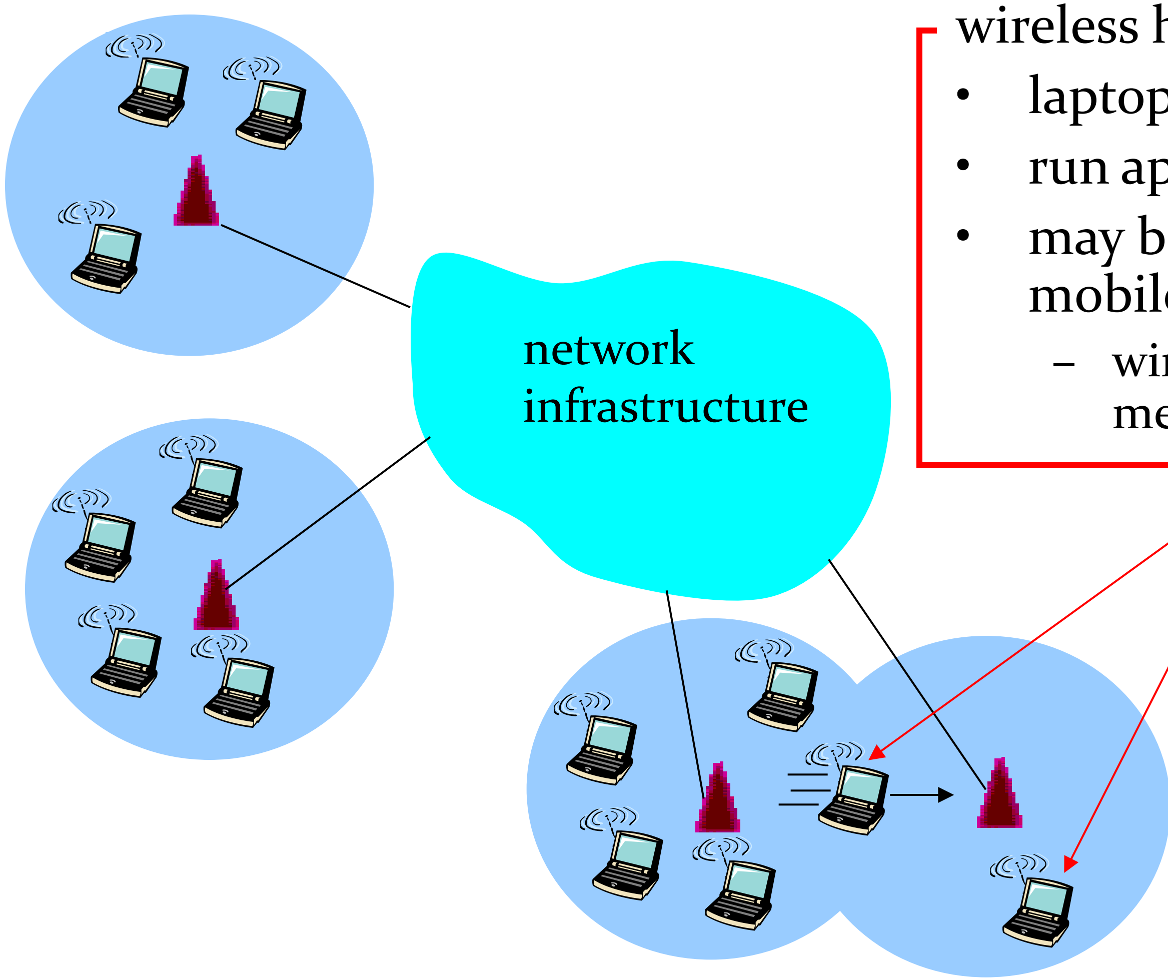
(Some) Benefits of Wireless Communication

- Convenience of untethered access
- Enables mobility, i.e., anytime, anywhere access
- Can reach areas where wired access solutions are expensive to deploy (e.g., satellite/wireless access for remote areas)
- Can be easier and faster to deploy
- Extend the reach of wired network infrastructure (e.g., mesh networks)
- Enable manifold app scenarios (e.g., Internet of Things)

Wireless Networks
Characteristics and Challenges

- Channel: path loss + shadowing + fading
  - Complex time-varying function of locations of communicating entities and the environment
- Multiple access interference
  - Wireless, a shared broadcast medium with possibility of spatial reuse
  - Receiver-side interference and hidden terminals
- Mobility
  - Handoff + location management for seamless access
- Energy
  - Mobile devices are battery powered
  - Battery energy density increase since 1990 by only a factor of three
    - ➢ Compare with 1200 times increase for disk capacity and several hundred times increase in CPU speed
  - Wireless interfaces among the major power consumers
- Security (e.g., eavesdropping concerns)

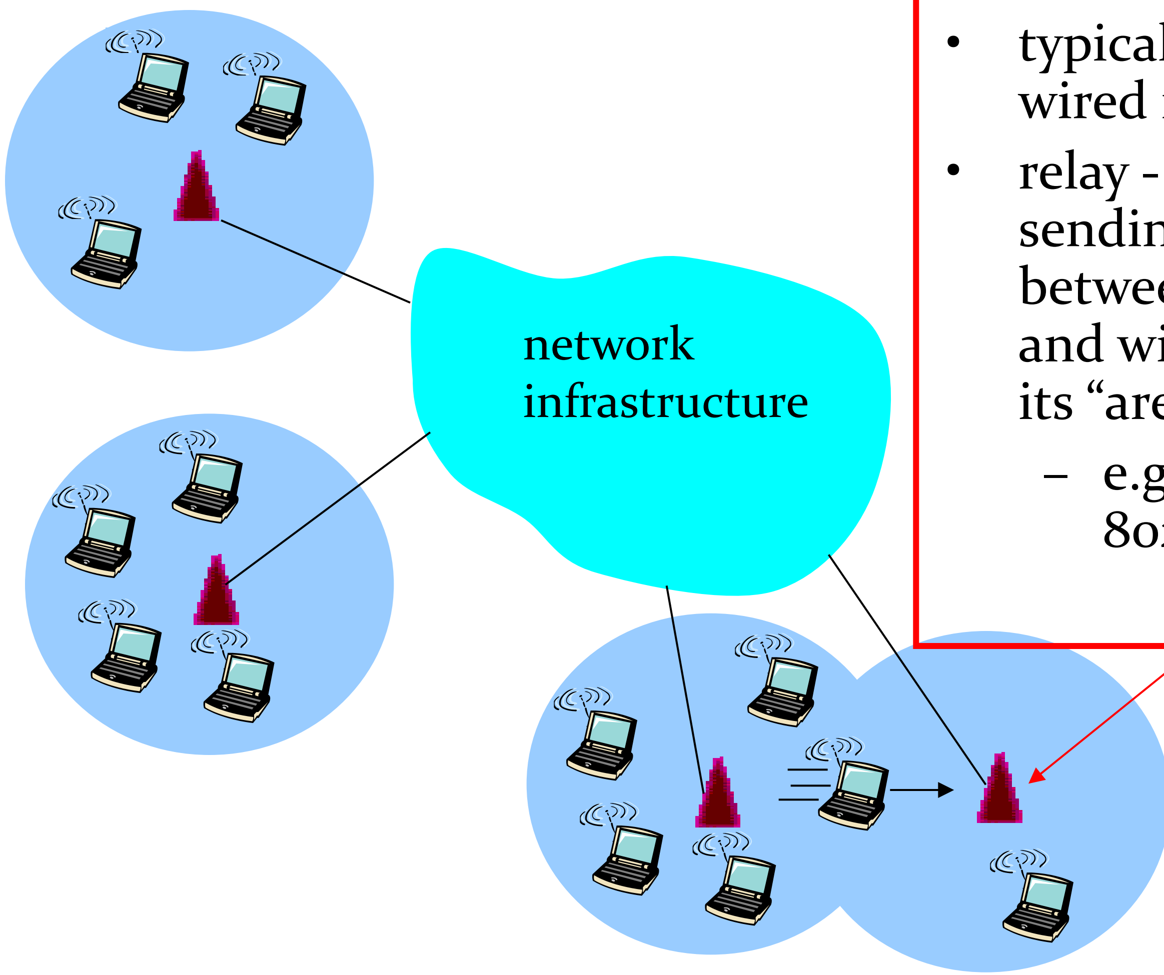
A Simple and Common Wireless Network Model



wireless hosts

- laptop, PDA, IP phone
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility

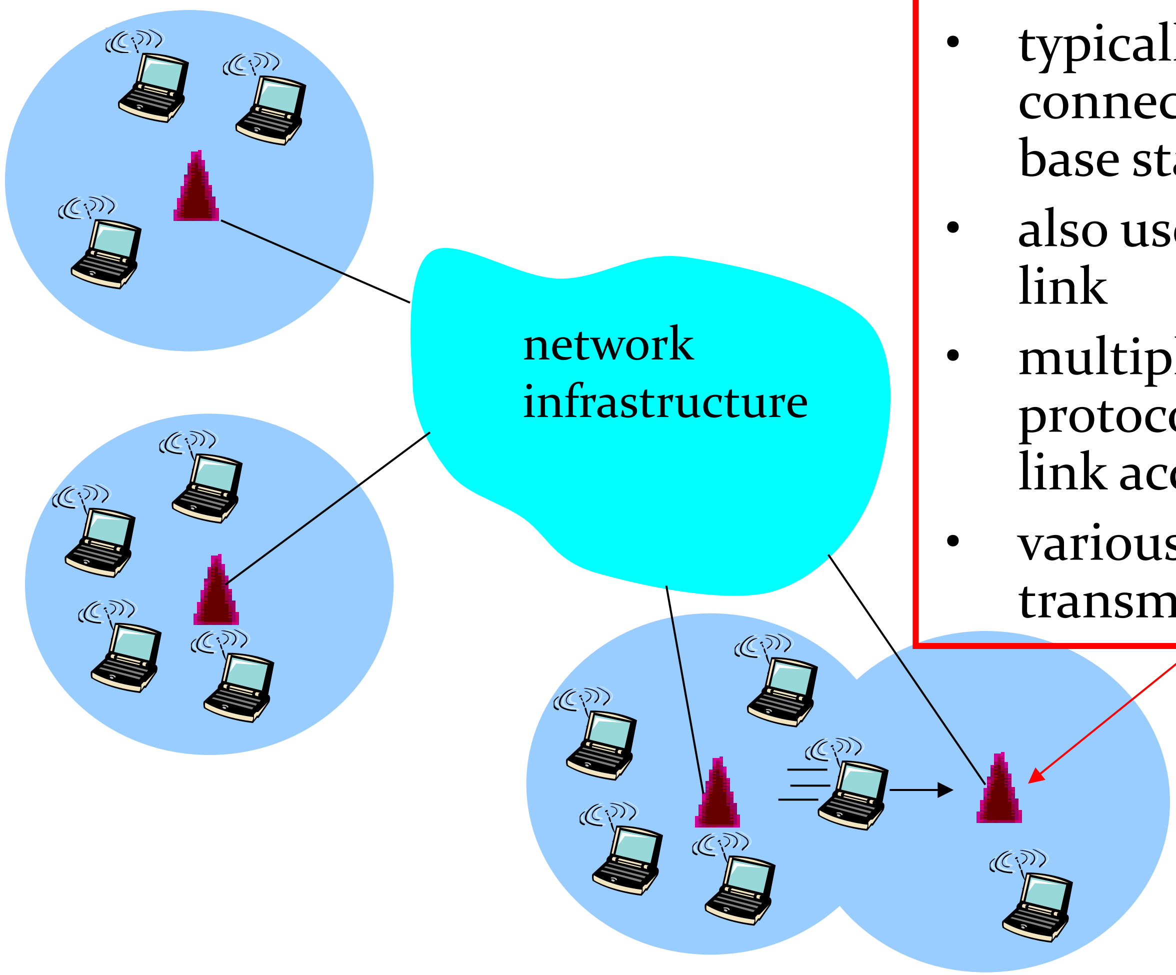
A Simple and Common Wireless Network Model



base station

- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers, 802.11 access points

A Simple and Common Wireless Network Model



wireless link

- typically used to connect mobile(s) to base station
- also used as backbone link
- multiple access protocol coordinates link access
- various data rates, transmission distance

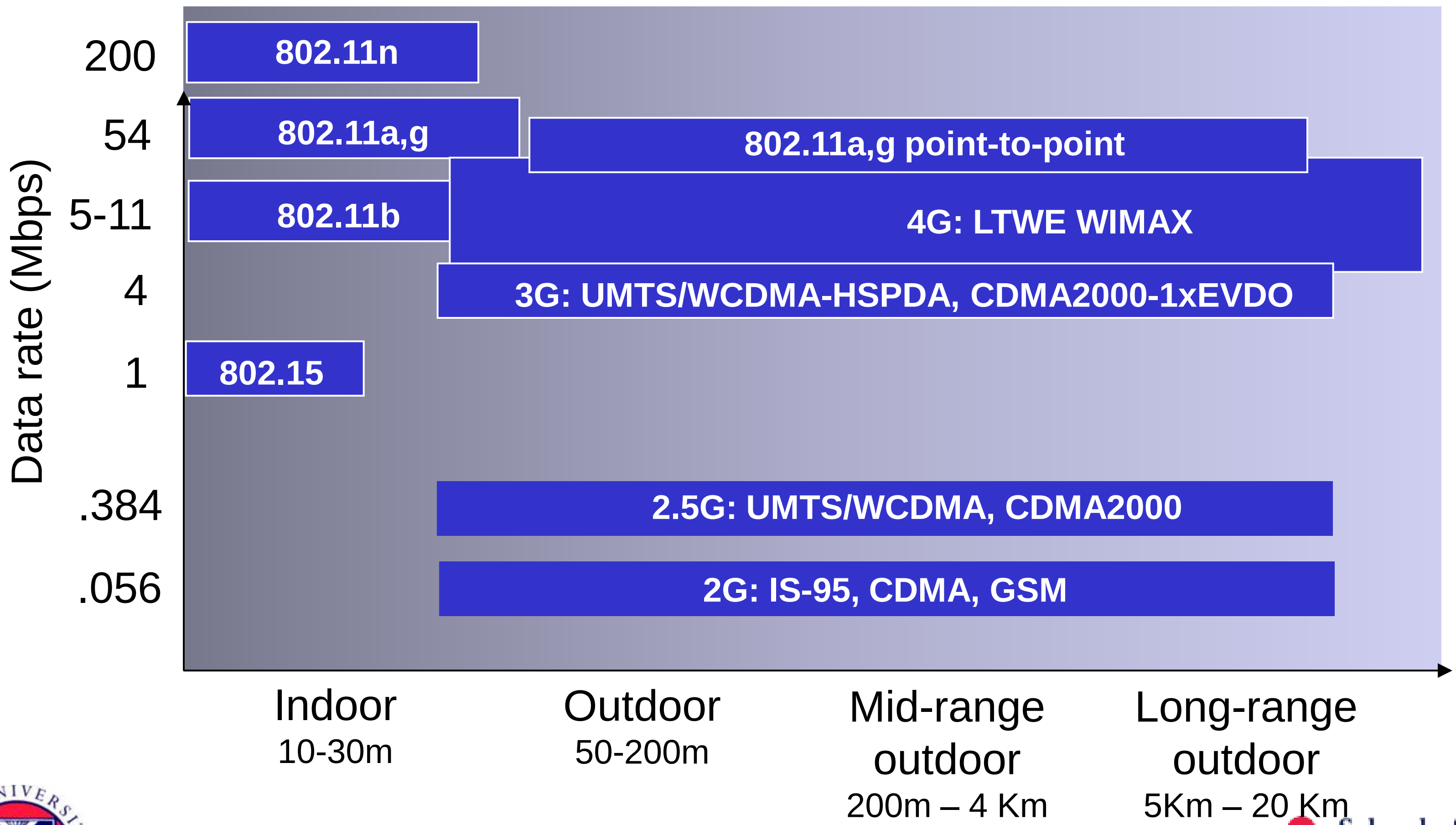
A Taxonomy of Wireless Networks

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, cellular, WiMax) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: *mesh net*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

Another Classification…

- Wide area wireless networks
  - Cellular (mobile phone and data) networks (e.g., 3G, 4G)
  - Broadband wireless access networks (e.g., WiMax, MMDS, LMDS)
  - Satellite networks
  - Paging systems
- Multihop wireless networks
  - Wireless mesh networks
  - Sensor networks
  - Mobile ad hoc networks (MANETs)
  - Vehicular ad hoc networks (VANETs)
- Wireless local area networks
  - WiFi/802.11, HIPERLAN/2, cordless phones
- Short-range wireless networks
  - Bluetooth (e.g., wireless headset for mobile phones)
  - Zigbee: low-cost, low-power sensor network applications
  - Ultrawideband: high-bandwidth applications (e.g., wireless USB)
  - RFID (e.g., Lothian bus cards)

Rate/Range Characteristics of Select Wireless Technologies



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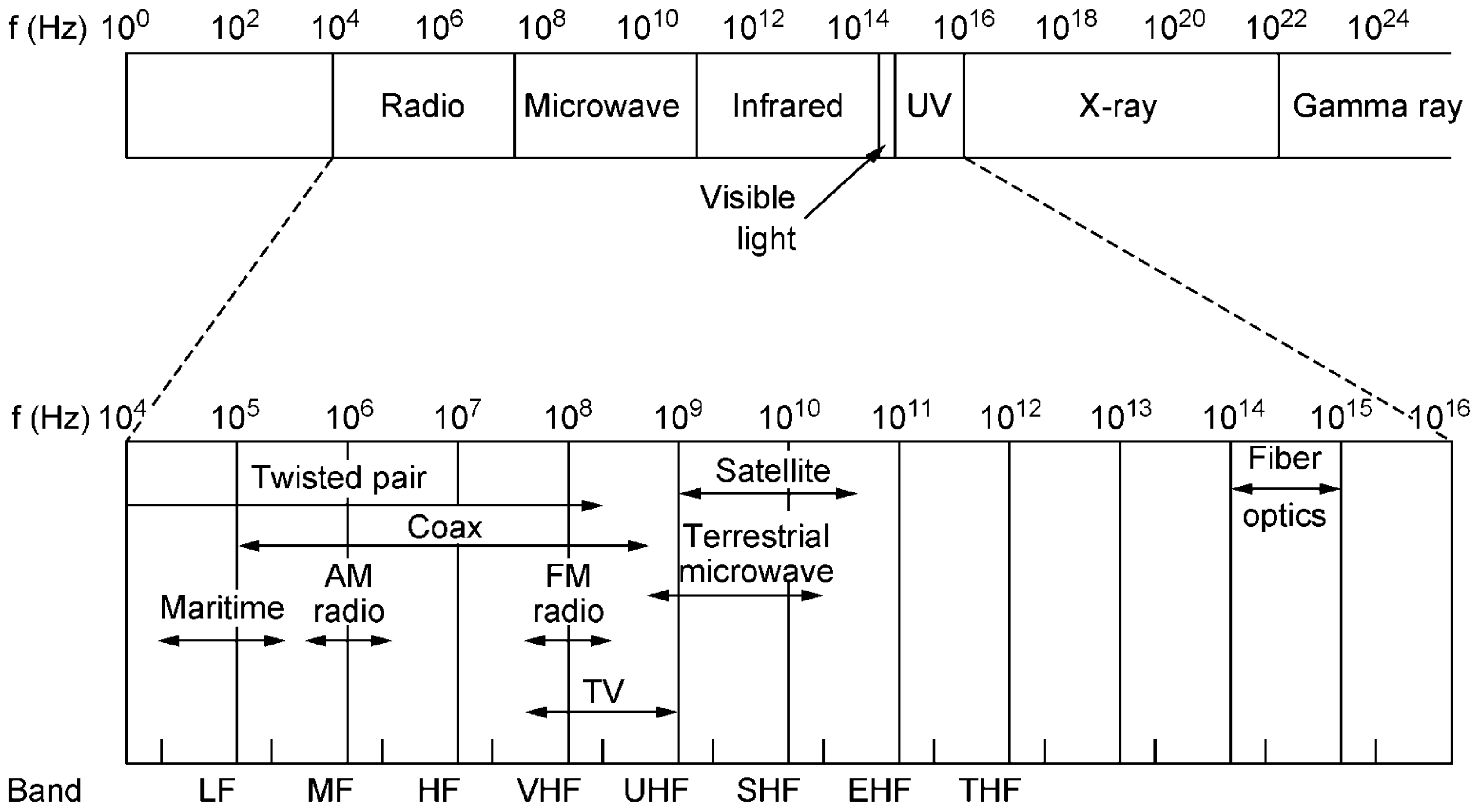
Other Classifications

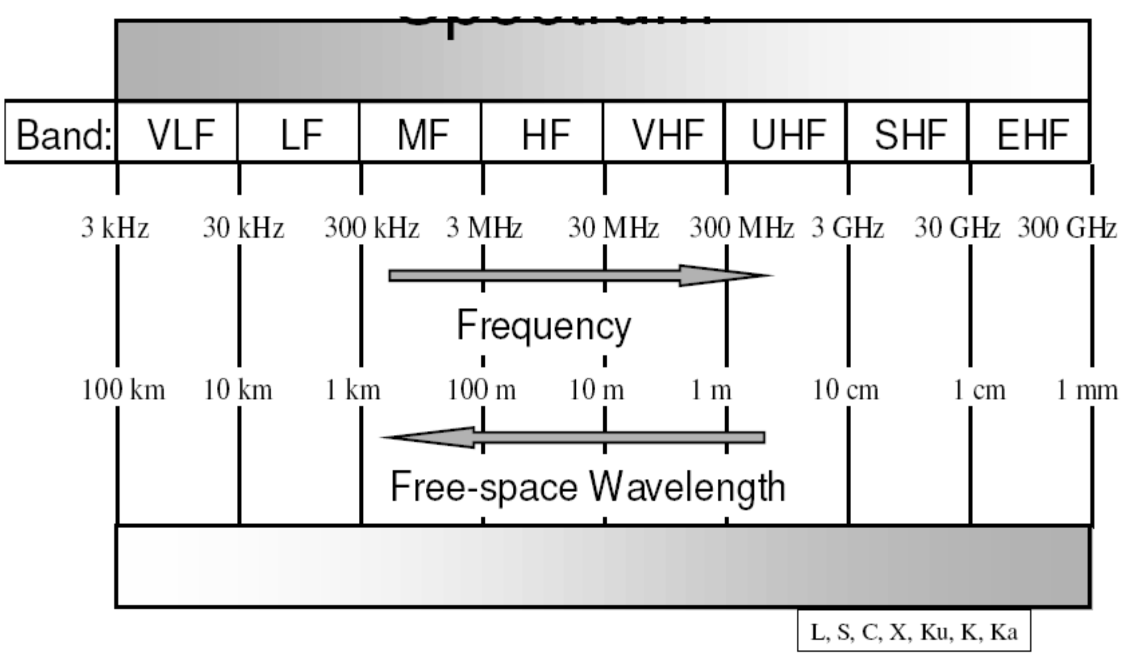
- Spectrum band used
- Spectrum access model (e.g., licensed, license-exempt)
- Amount of power allowed/consumed
- …

These classifications are not unrelated

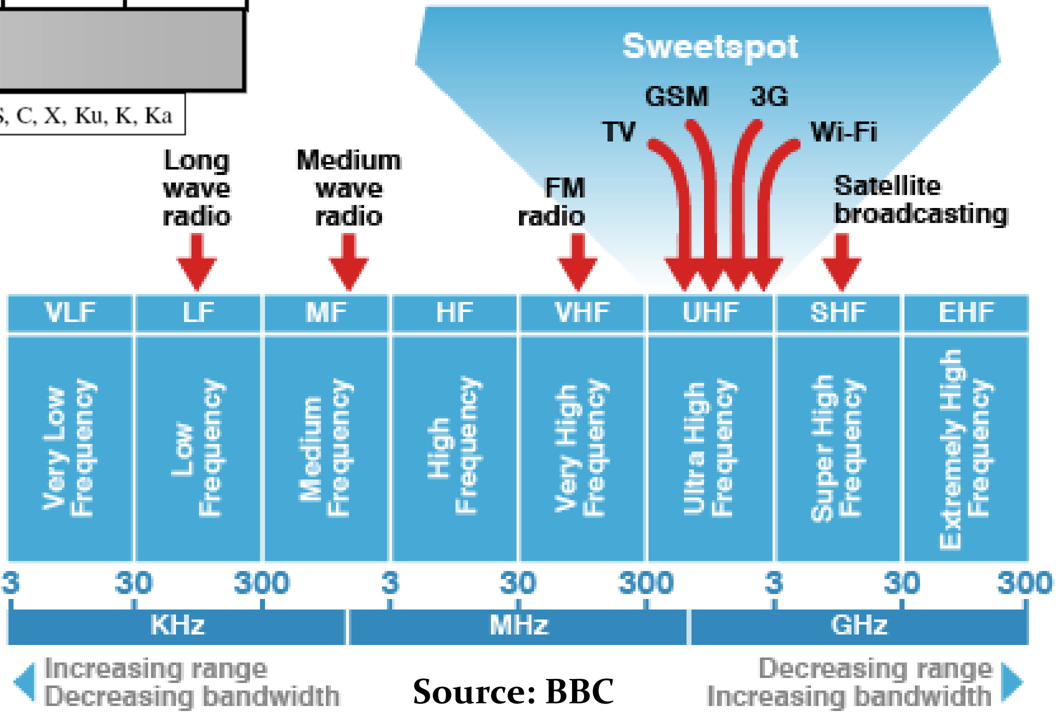
Electromagnetic Spectrum



Electromagnetic Spectrum (Contd.)

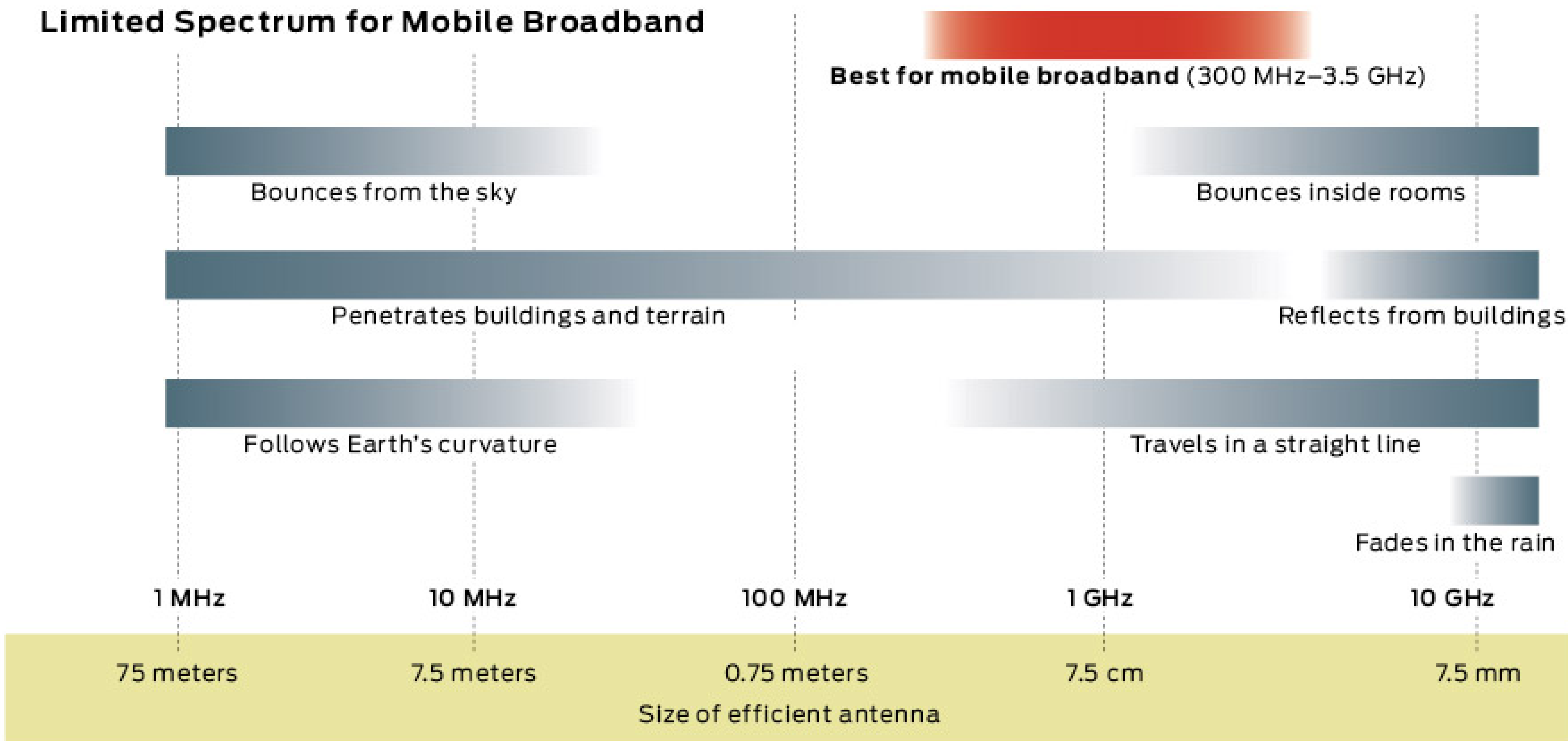


- Higher frequencies:
  - Larger bandwidths possible, smaller antennas
  - Range decreases as spreading loss increases and wavelength becomes smaller relative to obstructions



Source: BBC

Electromagnetic Spectrum (Contd.)



OPPORTUNITY WINDOW: The best frequencies for mobile broadband are high enough that the antenna can be made conveniently compact, yet not so high that signals will fail to penetrate buildings. This leaves a relatively narrow range of frequencies available for use [red band].

Recap

- Wireless devices and successful examples of wireless networks
- Benefits, characteristics and challenges of wireless communication
- Simple wireless network model representing Wi-Fi and cellular networks
- Various classifications of wireless networks, incl.
  - Single/multi Hop
  - (no)infrastructure
  - Range/coverage and rate
  - Based on spectrum band and access model used

Spectrum Regulation

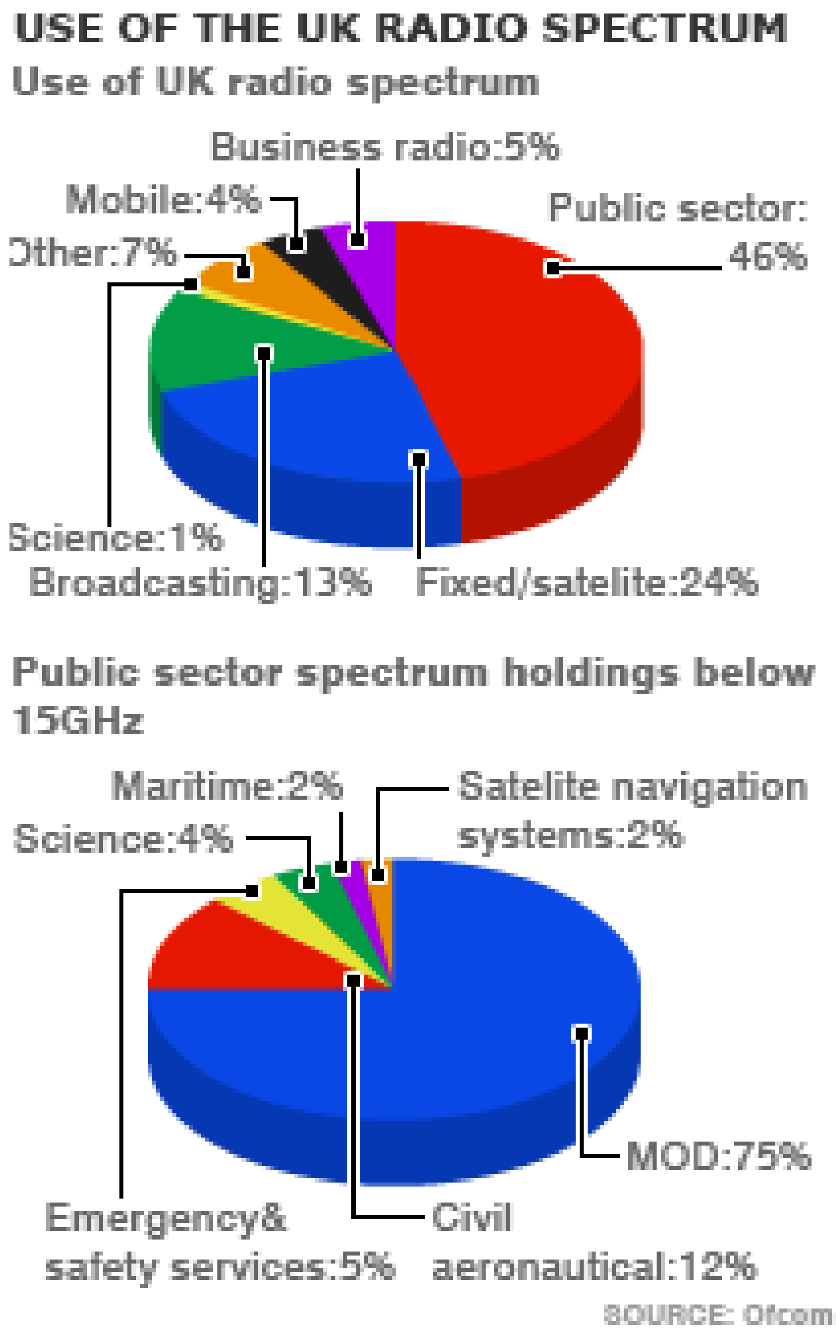
- Government agencies allocate and control the use of spectrum, only the prime portion (radio and microwave ranges)
  - UK: Office of Communications (Ofcom)
  - Europe: The European Conference of Postal and Telecommunications Administrations (CEPT)
  - US:
    - Commercial use: Federal Communications Commision (FCC)
    - Military use: Office of Spectral Management (OSM)
- Governments decide how much spectrum to allocate between commercial and military use
- Worldwide: ITU Radiocommunication (ITU-R) sector coordinates and harmonizes spectrum allocation
  - World Radiocommunication Conference (WRC)

Spectrum Allocation

- Bands for specific commercial uses – cellular, satellite, AM radio, FM radio, etc.

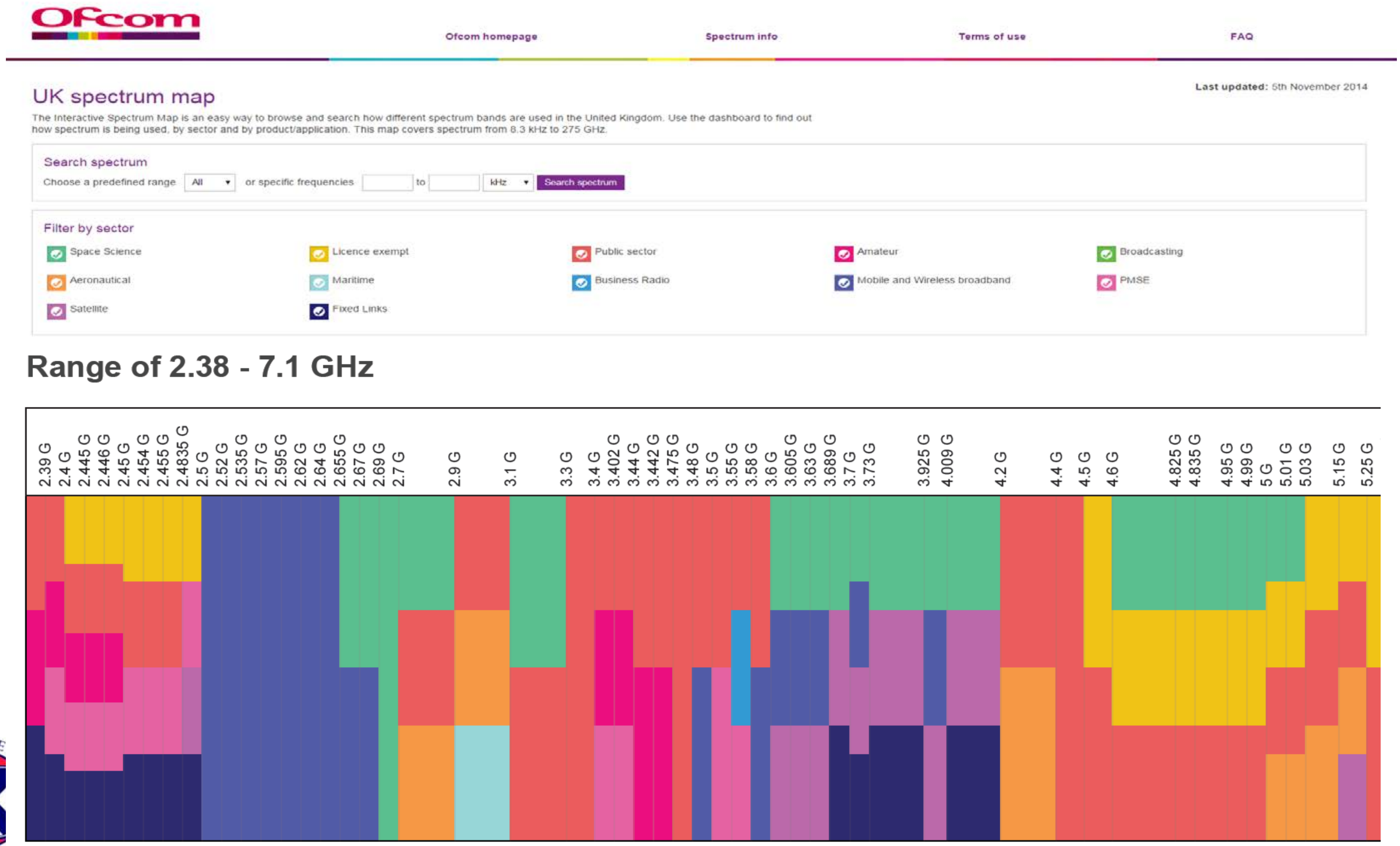
- Bands for license-exempt use (e.g., Wi-Fi)

- Bands for government/military use


USE OF THE UK RADIO SPECTRUM
Use of UK radio spectrum
Business radio:5%
Mobile:4%
Other:7%
Public sector:
46%
Science:1%
Broadcasting:13%
Fixed/satelite:24%
Public sector spectrum holdings below
15GHz
Maritime:2%
Satelite navigation
systems:2%
Science:4%
MOD:75%
Emergency&
safety services:5%
Civil
aeronautical:12%
SOURCE: Ofcom

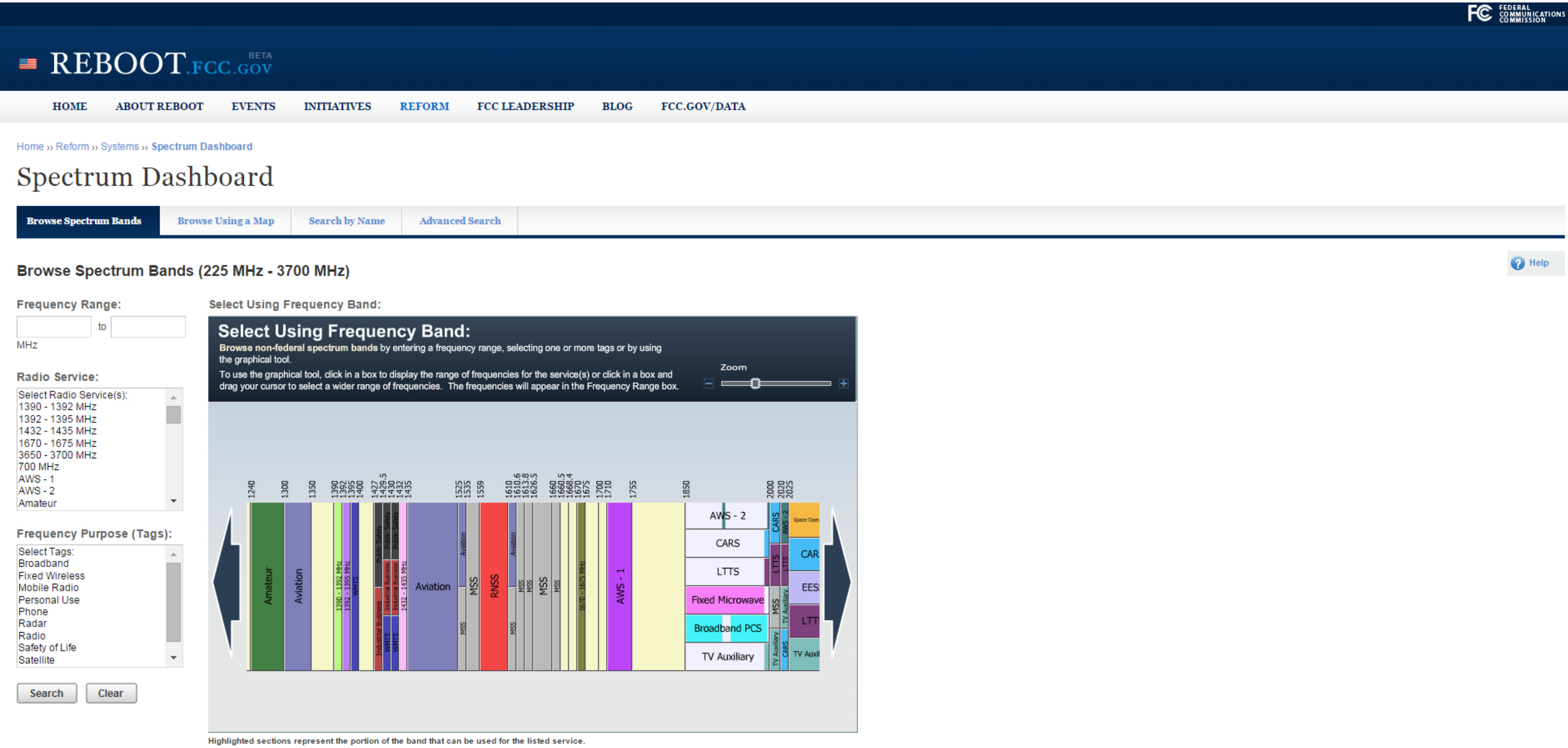
UK Spectrum Map

http://www.ofcom.org.uk/static/spectrum/map.html



US Spectrum Dashboard

http://reboot.fcc.gov/reform/systems/spectrum-dashboard



Spectrum Access Models

- Licensed or exclusive use spectrum
  - Past:
    1. Beauty Contest
       - Organizations interested in the spectrum make a proposal on serving public interest by getting a block of spectrum; regulator makes the "best" pick.
    2. Lottery
       - Hold a lottery for a spectrum block among interested organizations
  - Current:
    - Auctions (e.g., UK 4G spectrum auction in 2013)
      - Auction the spectrum block in question and give it to highest bidder

Spectrum Access Models

- License-exempt / Unlicensed / Spectrum Commons
  - E.g., 2.4GHz (WiFi, Bluetooth, ZigBee, …)
- License-Exempt White Space Access or Secondary Spectrum Commons
  - E.g., 5GHz WiFi, White spaces in TV bands
- Spectrum Underlay
  - operates as a secondary user in a frequency band with other primary users (e.g., UWB)
- Soft/Exclusive Secondary Licenses
  - Licensed/Authorized Shared Access (via leasing or rights transfer to secondary users)
  - Pluralistic Licenses
  - Overlay Auction Licenses

Example

US Licensed Spectrum Allocation

AM Radio	535-1605 KHz
FM Radio	88-108 MHz
Broadcast TV (Channels 2-6)	54-88 MHz
Broadcast TV (Channels 7-13)	174-216 MHz
Broadcast TV (UHF)	470-806 MHz
3G Broadband Wireless	746-764 MHz, 776-794 MHz
3G Broadband Wireless	1.7-1.85 MHz, 2.5-2.69 MHz
1G and 2G Digital Cellular Phones	806-902 MHz
Personal Communications Service (2G Cell Phones)	1.85-1.99 GHz
Wireless Communications Service	2.305-2.32 GHz, 2.345-2.36 GHz
Satellite Digital Radio	2.32-2.325 GHz
Multichannel Multipoint Distribution Service (MMDS)	2.15-2.68 GHz
Digital Broadcast Satellite (Satellite TV)	12.2-12.7 GHz
Local Multipoint Distribution Service (LMDS)	27.5-29.5 GHz, 31-31.3 GHz
Fixed Wireless Services	38.6-40 GHz

US Unlicensed Spectrum Allocation

ISM Band I (Cordless phones, 1G WLANs)	902-928 MHz
ISM Band II (Bluetooth, 802.11b WLANs)	2.4-2.4835 GHz
ISM Band III (Wireless PBX)	5.725-5.85 GHz
NII Band I (Indoor systems, 802.11a WLANs)	5.15-5.25 GHz
NII Band II (short outdoor and campus applications)	5.25-5.35 GHz
NII Band III (long outdoor and point-to-point links)	5.725-5.825 GHz

Standards

- Standards required for interoperable products and systems
- Also allow economies of scale and push down prices
- Some relevant standards development groups
  - IEEE (US)
  - 3GPP: collaboration between groups of telecoms associations incl. ETSI
  - IETF for Internet Standards (incl. those concerning wireless and mobile networking)
  - ITU
  - ISO
- Standardization process imperfect and political
  - Participants often have an agenda that conflicts with what is best
  - Can take a long time
  - Difficult to change once widely adopted

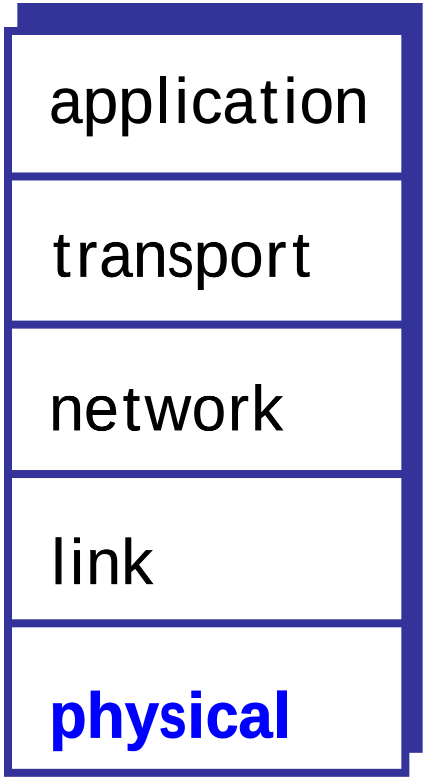
An Overview of Wireless Communication

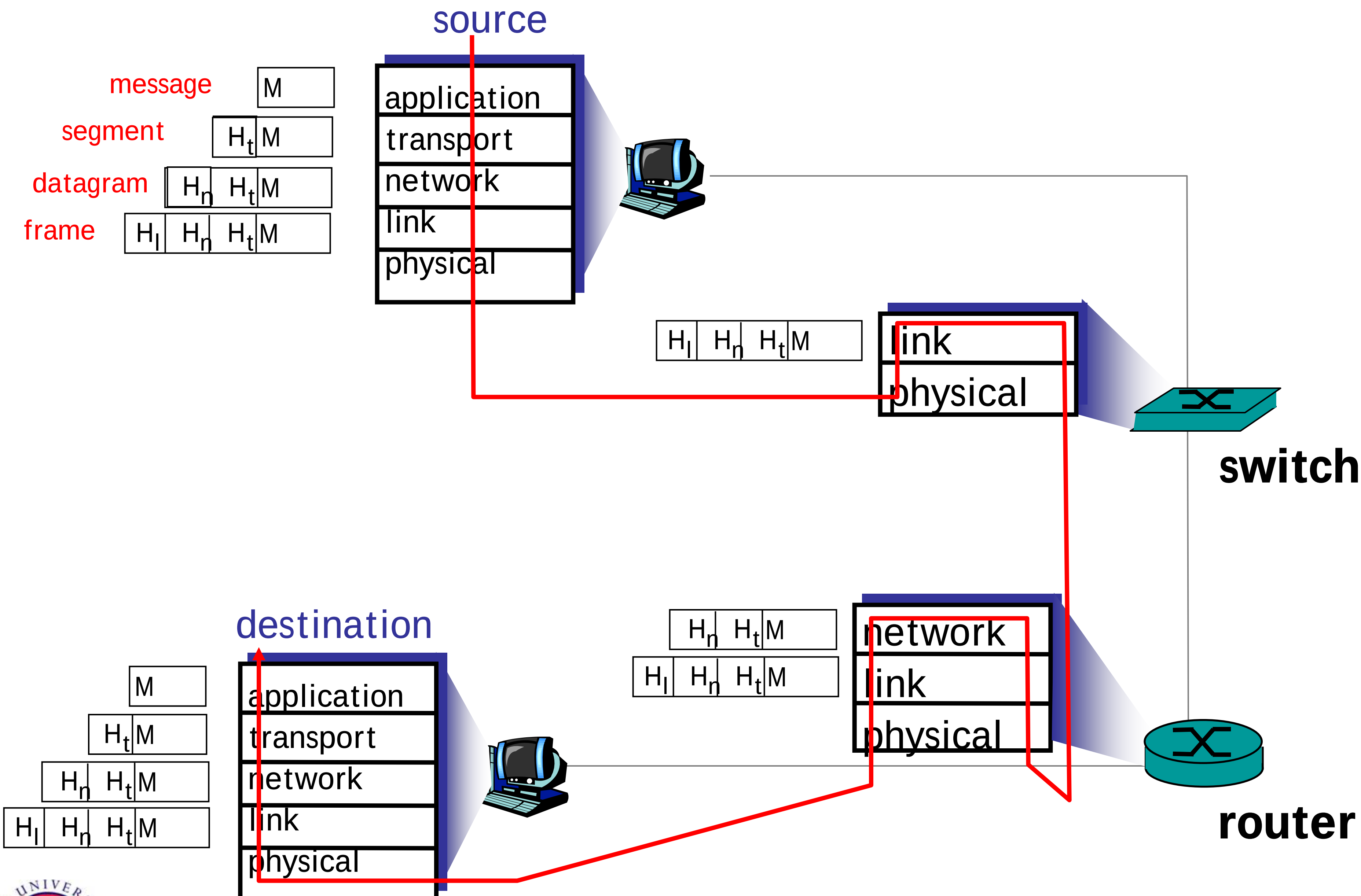
Plan

- Initially, focus on a single wireless link
  - Operating on a small slice of spectrum called a "channel", defined by a centre frequency and channel width
- Then, multiple access

Internet Protocol Stack

- application: supporting network applications
  - FTP, SMTP, HTTP
- transport: process-process data transfer
  - TCP, UDP
- network: routing of datagrams from source to destination
  - IP, routing protocols
- link: data transfer between neighboring network elements
  - PPP, Ethernet
- physical: bit pipe





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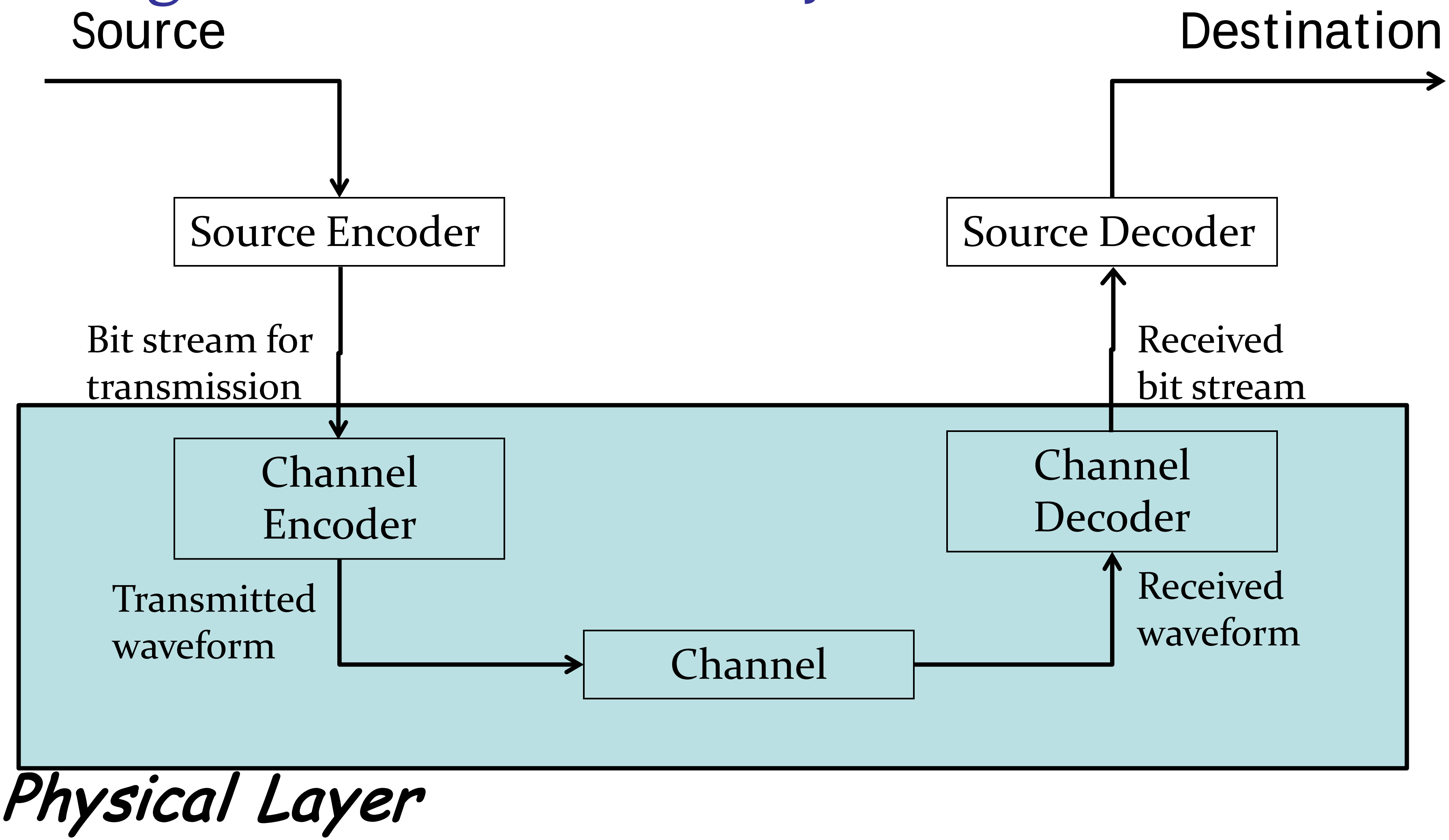
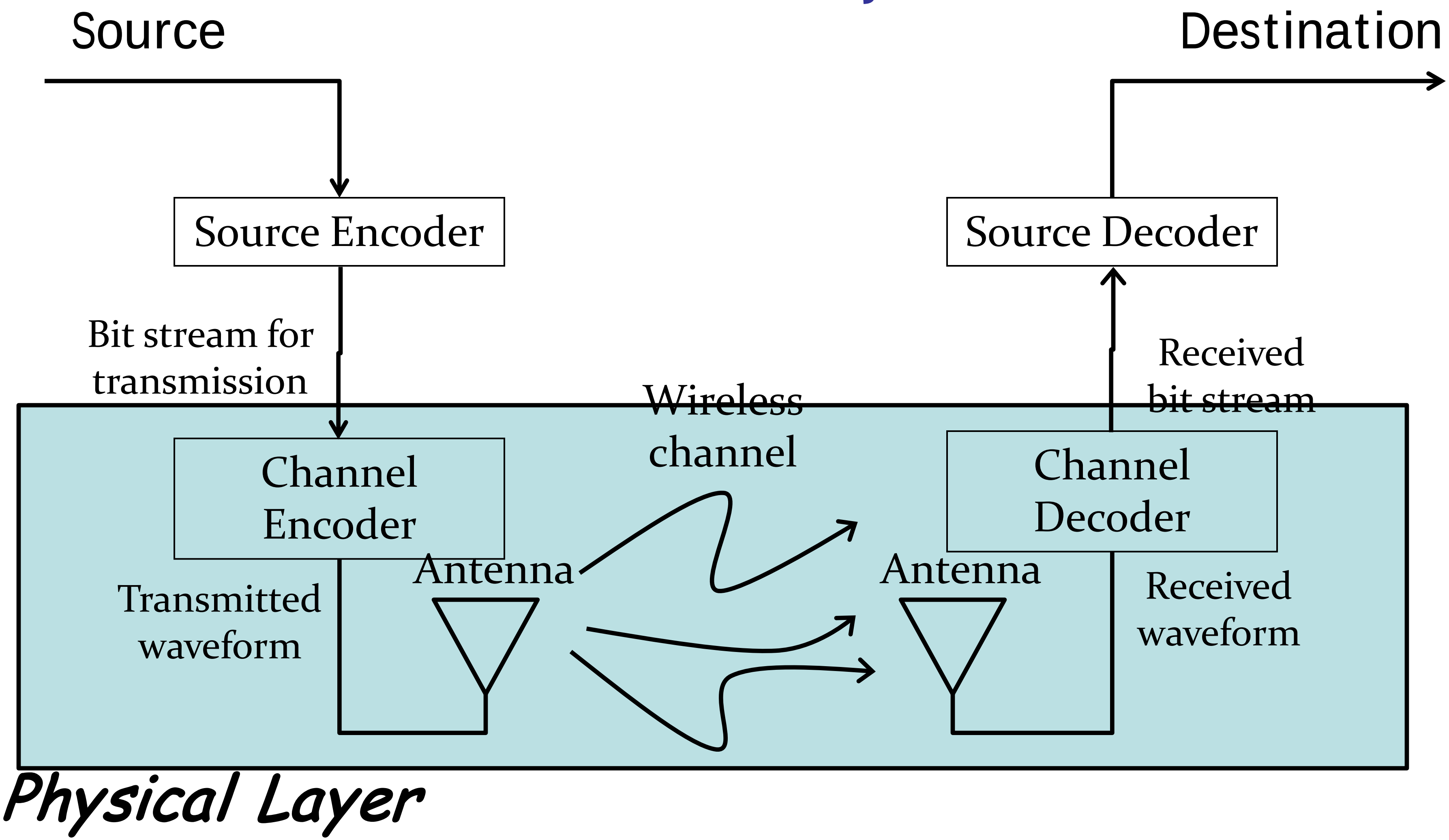
Digital Communication System



Channel Encoder/Decoder Layers

1. Error Correction Coder/Decoder
2. Modulator/Demodulator (Baseband)
3. Frequency Conversion (Passband)

Wireless Communication System



Digression: Decibel Notation

Decibels

- Why use decibel units?
  - Signal strength often falls off exponentially, so loss easily expressed in terms of decibel (a logarithmic unit)
  - Net gain or loss via simple addition and subtraction

- Power ratio in decibels = $10\log_{10}(P/P_{ref})$
  - Power ratios 10^1 → 10dB, 10^2 → 20dB, 10^3 → 30dB, …
  - Similarly, power ratios 10^{-1} → -10dB, 10^{-2} → -20dB, 10^{-3} → -30dB, …
  - 3dB (power ratio = 2), -3dB (power ratio = ½)
  - Voltage ratio in decibels = $20\log_{10}(V/V_{ref})$, since $P = V^2/R$

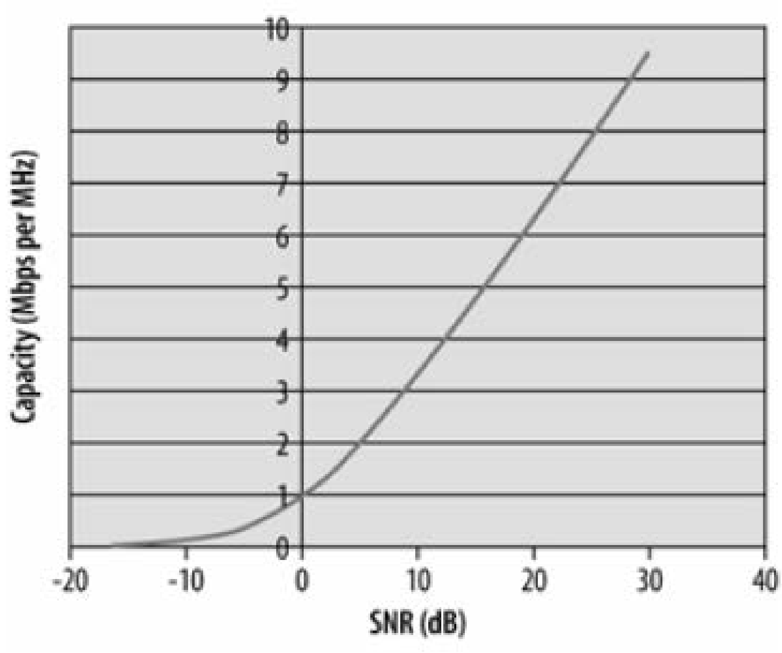
Decibels (Contd.)

- Absolute power with respect to standard reference power in decibels: dBW (P_{ref} = 1W) and dBm (P_{ref} = 1mW)
  - 1W = 0 dBW = +30 dBm; 1mW = 0 dBm = -30 dBW
- Antenna gains: dBi (P_{ref} is power radiated by an isotropic reference antenna) and dBd (P_{ref} is power radiated by a half-wave dipole)
  - 0 dBd = 2.15 dBi
- dB for gains and losses (e.g., path loss, SNR)

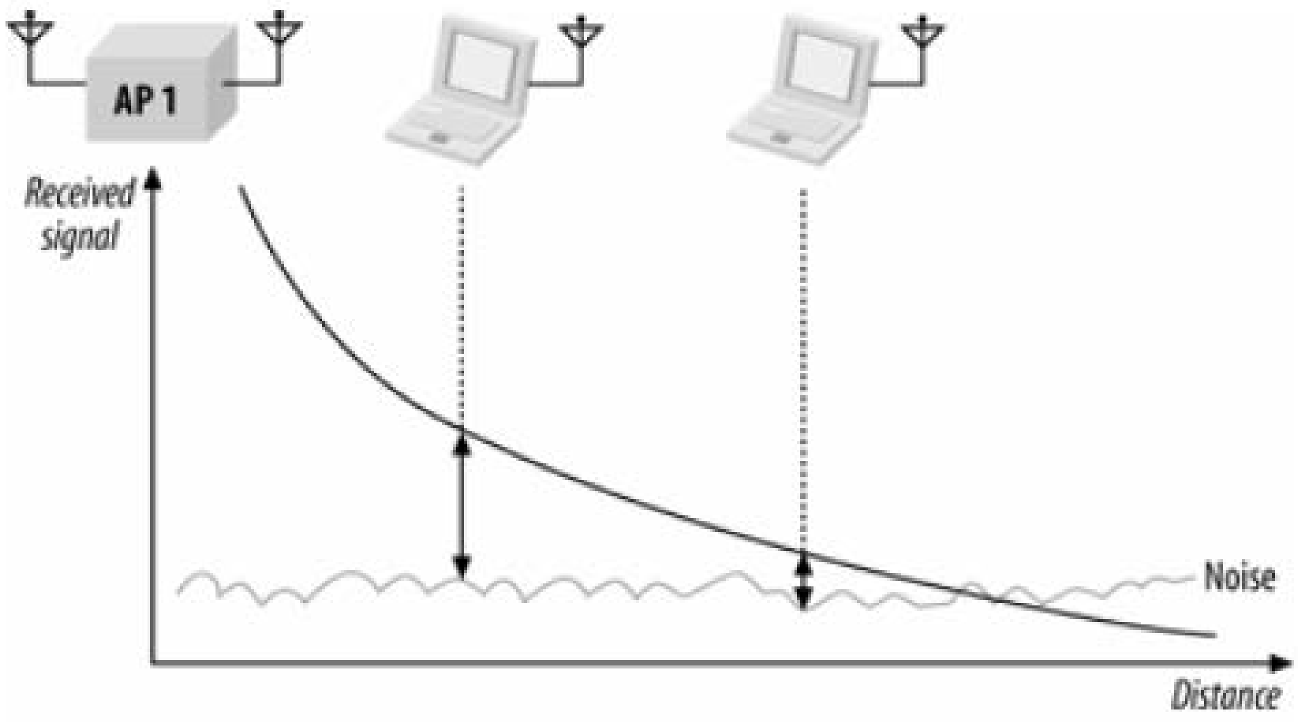
End of Digression

Signal-to-Noise Ratio (SNR)

- Crucial factor determining wireless transmission quality
- Shannon's Channel Capacity Theorem for band-limited additive white Gaussian noise (AWGN) channel: $C = W \log_2(1+SNR)$
  - C, channel capacity in bits per second
  - W, channel bandwidth in Hz
  - SNR, signal-to-noise ratio
- So long as data rate below C, error probability can made arbitrarily lower with the use of more sophisticated coding (error correction) schemes



SNR versus Distance



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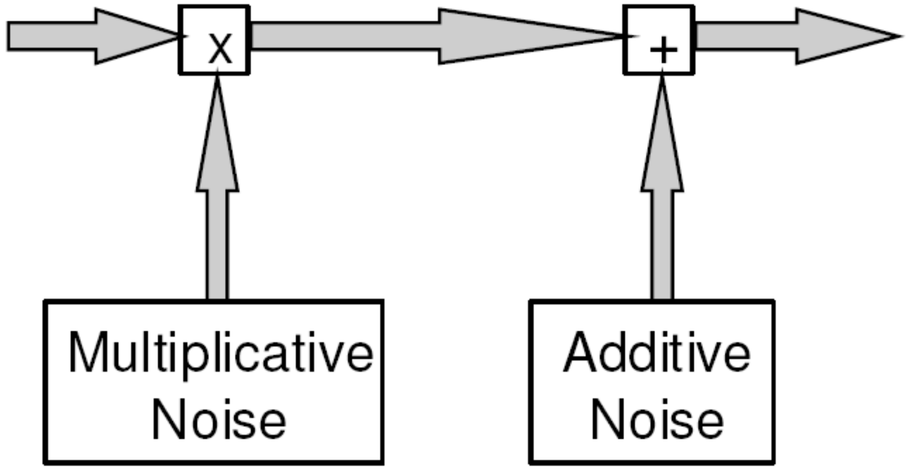
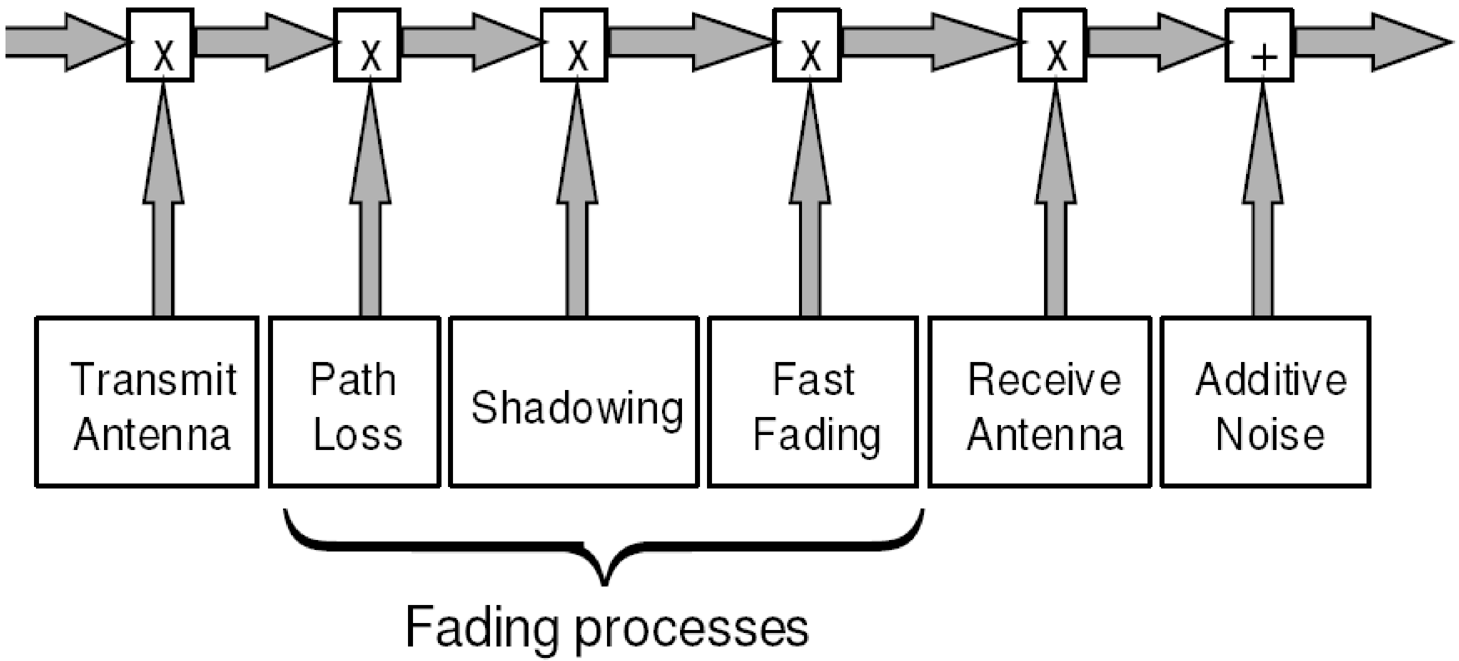
Wireless Channel

Noise Types in a Wireless Channel



- Multiplicative
  - Antenna directionality
  - Attenuation from absorption (walls, trees, atmosphere)
  - Shadowing
  - Reflection (smooth surfaces)
  - Scattering (rough surfaces and small objects)
  - Diffraction (edges of buildings and hills)
  - Refraction (atmospheric layers, layered/graded materials)
- Additive
  - Internal sources within the receiver (e.g., thermal noise)
  - External sources (e.g., interference from other transmitters and appliances)

Three Scales of Multiplicative Noise



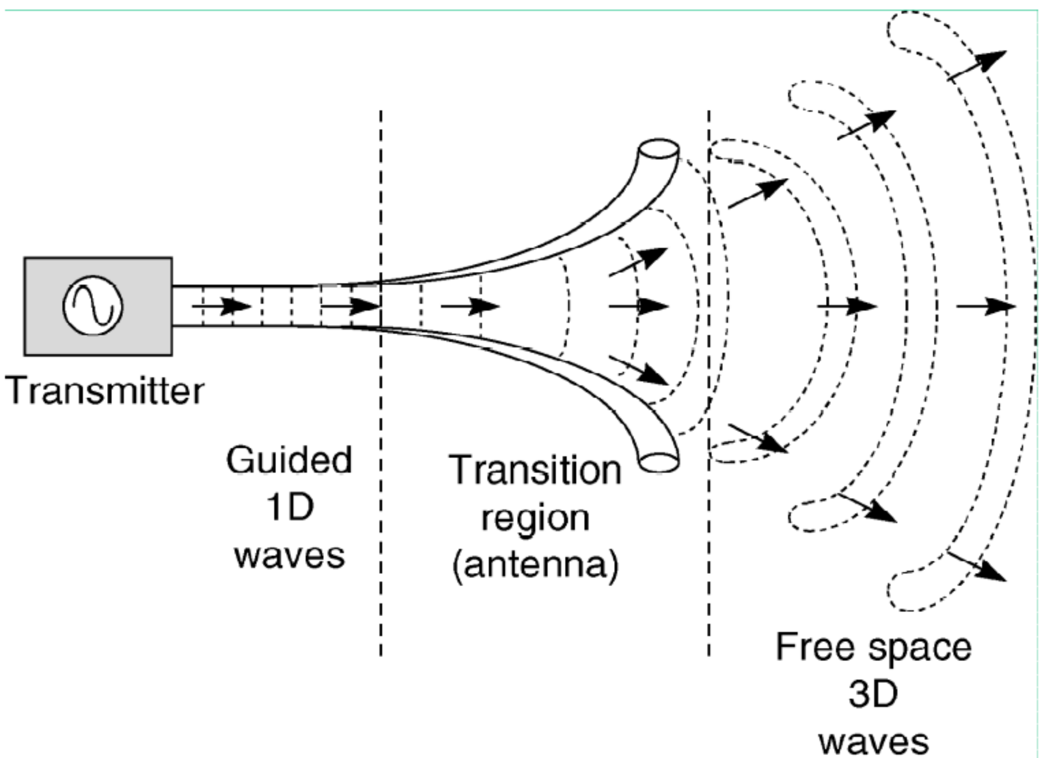
- Large and medium scale propagation effects
  - Path loss
  - Shadowing leads to variations over distances in the order of metres
    - ➢ Could be over 10s or 100s of metres in outdoor environments

- Small-scale fading (or multipath fading): causes variations of over very short distances in the order of the signal wavelength

Antennas

Antenna Design Goal

- Ensure the process of conversion between electrical signal and electromagnetic wave is efficient, i.e., direct as much power as possible in "useful" directions



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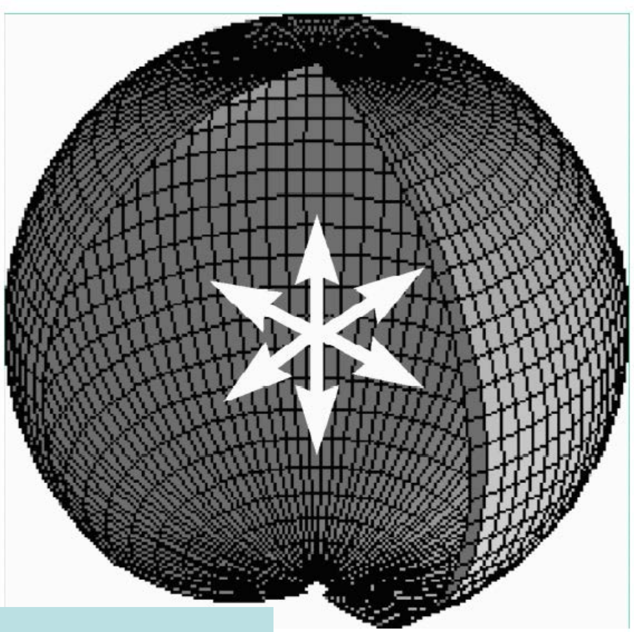
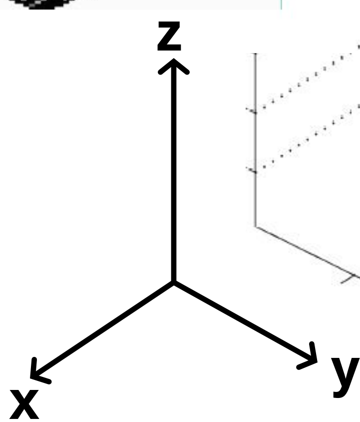
Antenna Radiation Pattern

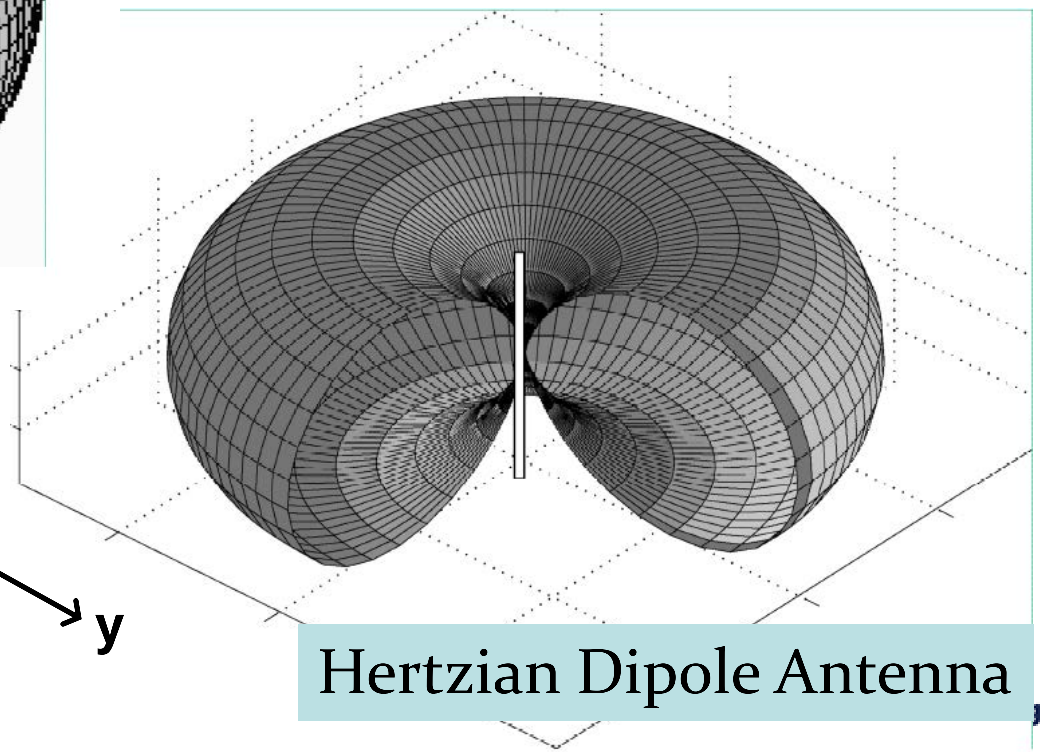
- Plot of far-field radiation from the antenna
  - Radiation intensity, U: power radiated from an antenna per unit solid angle
- Azimuth plane (x-y plane), Elevation plane (x-z plane)
- Different types of antennas have different radiation patterns
  - An ideal isotropic antenna has a spherical pattern
  - Omnidirectional (e.g., hertzian dipole) antenna has a donut shaped pattern
  - Directional antennas radiate power along a direction

Antenna Radiation Pattern (Contd.)



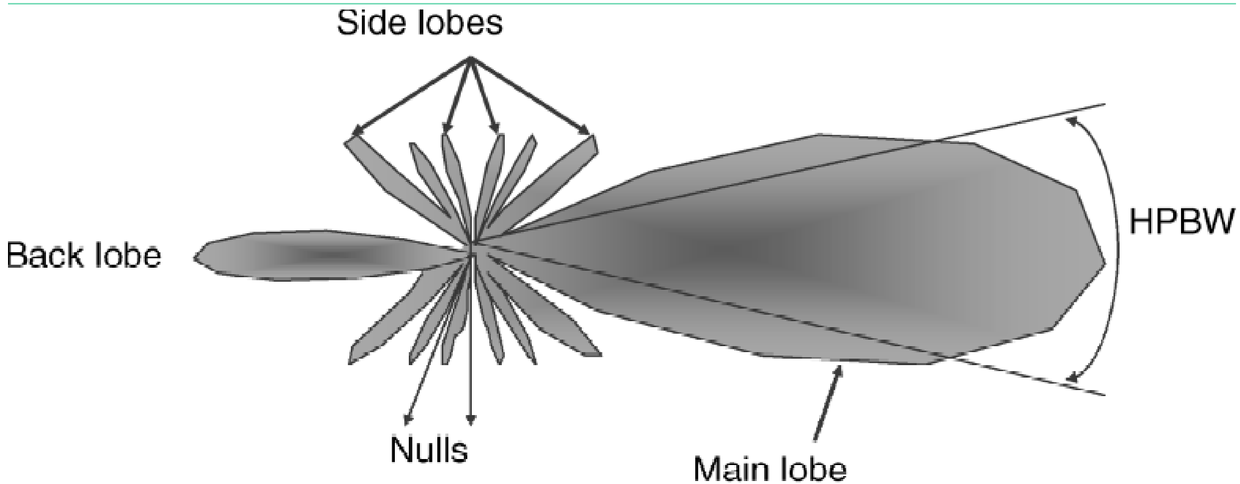
Isotropic Antenna





Hertzian Dipole Antenna

Radiation Pattern of a Generic Directional Antenna



- <u>Half-power beamwidth (HPBW):</u> angle subtended by the half-power points of the main lobe
- <u>Front-back ratio:</u> ratio between peak amplitudes of main and back lobes
- <u>Side lobe level:</u> amplitude of the biggest side lobe

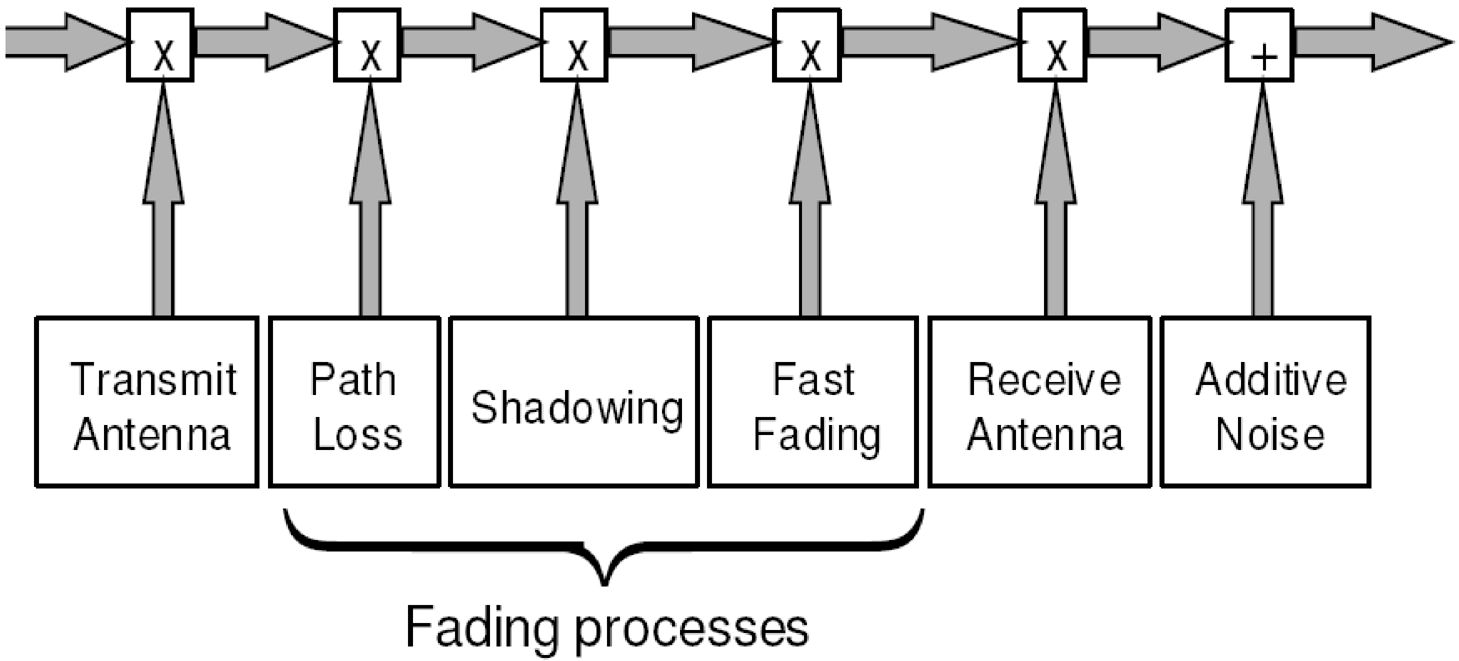
Gain and Other Antenna Characteristics

- **Directivity, D:** ratio of max radiation intensity of antenna to radiation intensity of isotropic antenna radiating the same total power

  $D = \sim 41{,}000/\Theta^{o}_{HP}\varphi^{o}_{HP}$; Θ^{o}_{HP} (φ^{o}_{HP}) are vertical (horizontal) plane half-power beamwidths in degrees

- **Radiation Efficiency, e:** ratio of radiated power to power accepted by antenna
  - Sometimes specified via Voltage Standing Wave Ratio (VSWR)
- **Antenna Gain, G = e * D**
  - Effective area of an antenna is a related concept we will see later
- Antenna polarization: orientation of the electric field of an electromagnetic wave relative to the earth
  - Linear (vertical/horizontal) vs. Circular antenna polarizations

Three Scales of Multiplicative Noise



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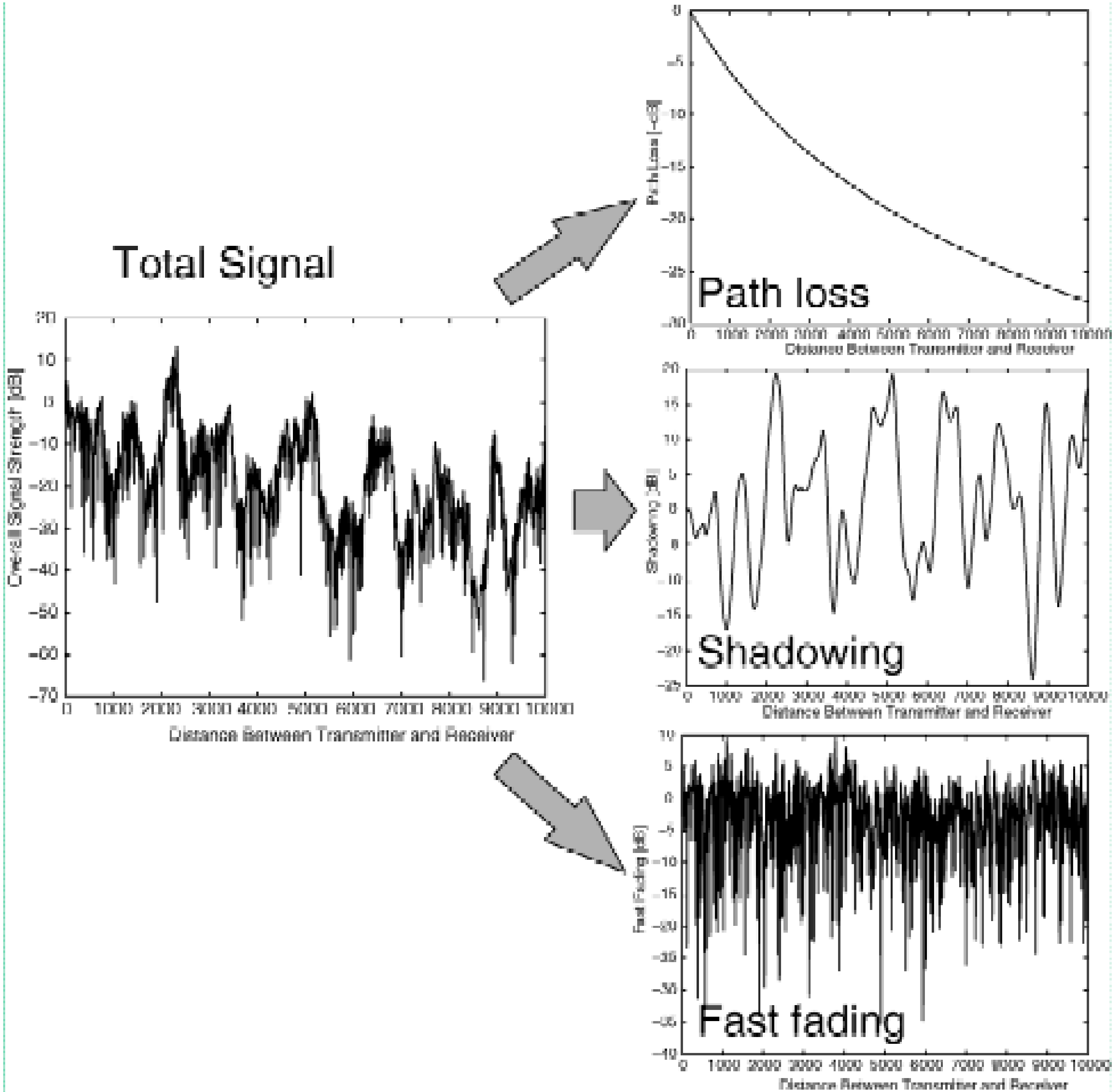
Fading Processes Illustrated



Another Illustration of Path Loss, Shadowing and Multipath Fading